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THE METROPOLITAN DISTRICT WATER SUPPLY TUNNEL FROM THE WARE RIVER TO THE WACHUSETT RESERVOIR

FRANK E. WINSOR,* Member

(Presented at a meeting of the Boston Society of Civil Engineers, October 19, 1932)

THE WATER DISTRICT

THE metropolitan water district, as established originally in 1895, included the cities of Boston, Chelsea, Everett, Malden, Medford, Newton and Somerville, and the towns of Hyde Park (now a part of Boston), Belmont, Melrose, Revere, Watertown and Winthrop, and provided that any city or town having any part of its area within ten miles of the State House might join the district under the conditions prescribed.

The city of Quincy and the towns of Arlington, Brookline, Lexington, Milton, Nahant, Stoneham and Swampscott have since joined the district, so that there are now twenty municipalities in the district with a combined population of about 1,500,000, and fifteen other municipalities, namely, Braintree, Cambridge, Canton, Dedham, Hingham, Hull, Lynn, Needham, Saugus, Wakefield, Waltham, Wellesley, Weymouth, Winchester and Woburn, with a combined population of about 400,000, which are entitled to join at any time they may elect to do so.

THE METROPOLITAN SYSTEM

The metropolitan water system, as virtually completed some twenty-five years ago, except for distribution mains which have been increased as required, includes Cochituate Lake and Aqueduct (1848), the Sudbury Aqueduct and eight storage reservoirs (1872-99), the

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Wachusett Reservoir and the Wachusett and Weston aqueducts (1895-1906), equalizing reservoirs at Chestnut Hill (1868), Spot Pond (1900), Weston (1905), various standpipes, distribution mains now totaling about one hundred and seventy miles in length, etc.

The total cost of the metropolitan system, including about \$14,000,000 paid for existing works mainly in the city of Boston but not including expenditures for the new works hereinafter described, is about \$47,500,000. The total consumption from metropolitan sources is about 140,000,000 gallons daily, and the combined consumption of the fifteen municipalities now using their own supplies but entitled to join the district is about 30,000,000 gallons daily. For the past twenty-five years or more the Wachusett Reservoir has been the main source of supply of the district. This reservoir has a flow line 395 feet above Boston City Base (approximately mean low water in Boston Harbor). Water is dropped through a power plant into the Wachusett Aqueduct thence into the Sudbury Reservoir at elevation 260, thence through a power plant into the Weston Aqueduct to the Weston Reservoir at elevation 200, thence to Spot Pond at elevation 163 or Chestnut Hill at elevation 134. Water is also brought to Chestnut Hill Reservoir through the Sudbury and Cochituate aqueducts, as required.

THE NEW SUPPLY

The need of a major addition to the water supply became evident fully fifteen years ago, and as a result of investigations by two commissions, one of which reported in 1922 and the other in 1926, legislation was enacted in 1926-27 which established the Metropolitan District Water Supply Commission, and gave it authority to build the new works, such works to be turned over to the Metropolitan District Commission for operation when completed. Legislation made provision for the development for emergency use of certain waters from the Sudbury system, which had been little used for many years, for the diversion for water supply of the flood waters of the Ware River and for the use of the greater part of the waters of the Swift River, to be accomplished by the construction of a large reservoir on the Swift River about ten miles above its junction with the Chicopee. This reservoir has been named Quabbin Reservoir. The name Quabbin is of Indian origin. Quabbin Mountain is the highest elevation of any of the peaks in the vicinity, and much of the territory to be submerged was known in late colonial times as Quabbin. The drainage areas involved for both the present and proposed supplies are shown on the accompanying Plate I.

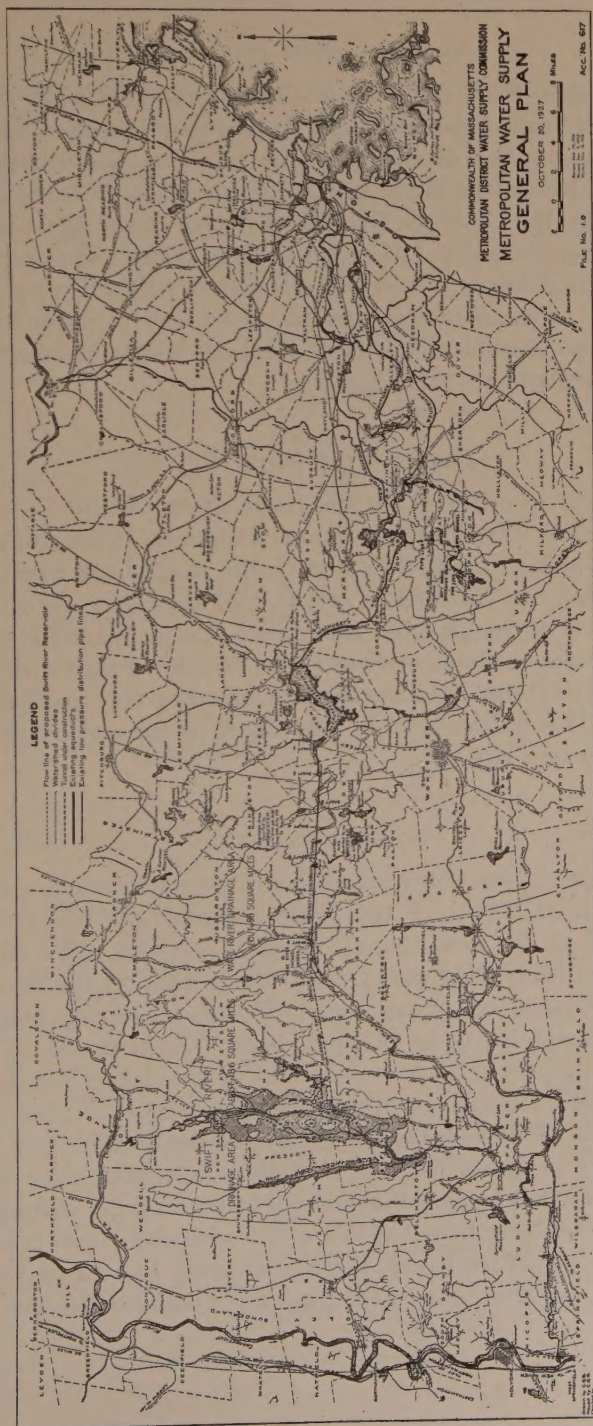


PLATE I

LITIGATION WITH CONNECTICUT

In January, 1928, the State of Connecticut filed a bill of complaint in the United States Supreme Court seeking to enjoin the Commonwealth of Massachusetts for diverting any water from the watershed of the Connecticut River (the Ware and Swift rivers flow into the Connecticut River through the Chicopee River). A decree of the court in February, 1931, sustained the right of Massachusetts to take these waters as authorized by the Legislature, subject to restrictions of the United States War Department. Details of this case may be found in paper by Frank E. Winsor in the Journal of the New England Water Works Association, Vol. XLV, September, 1931.

TWENTY-FIVE MILE TUNNEL

The water from the Ware and Swift rivers will be conveyed to the Wachusett Reservoir through a tunnel 24.6 miles in length, to be called Quabbin Aqueduct. The flow line of the Wachusett Reservoir is 261 feet lower than the Ware River intake, and 135 feet lower than the proposed flow line of the Quabbin Reservoir. As the Ware River water will enter the tunnel at about midway of its length through a shaft 252 feet deep, it may be stored in either the Wachusett or the Quabbin reservoirs, as desired. This is illustrated by the tunnel profile and by the hydraulic gradient lines on Plate II.

TUNNEL CONSTRUCTION

This paper is concerned mainly with the construction and operation (since March 21, 1931) of the Ware River works which include the easterly half of the new tunnel, namely, fourteen miles of hard rock tunnel driven from eight shafts, a diversion dam on the Ware River in the town of Barre, and minor appurtenances. The organization of the engineering corps began in October, 1926. Construction of the tunnel began with the execution of a contract for the deepest shaft (656 feet) in March, 1927, followed by the letting of contracts for five other shafts in July, 1927. Following the completion of these shafts and the excavation of short adjacent lengths of tunnel, contracts were executed in April, 1928, for the entire tunnel, about fourteen miles in length (including one mile westerly from the Ware River intake), from the Wachusett Reservoir to the Ware River, the tunnel being located and designed so as to permit an extension to the proposed Quabbin Reservoir. A plan

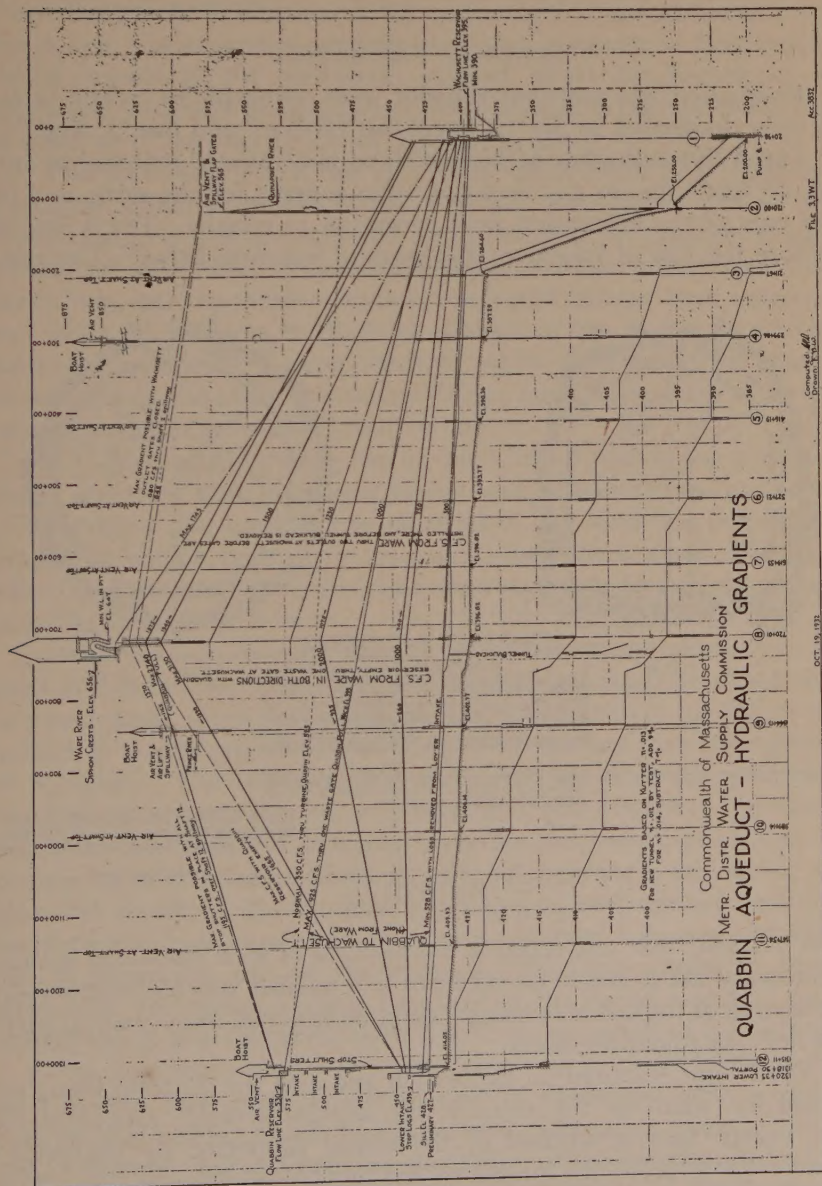


PLATE II

SECT. 19, 1911

FILE 1117

NO. 301

Computed by
J. H. Brown

Commonwealth of Massachusetts
METR. DIST. WATER SUPPLY COMMISSION
QUABBIN AQUEDUCT - HYDRAULIC GRADIENTS

12 inches outside the A line; in arch and side walls of unsupported sections of tunnel, 12 inches outside the A line. In invert, 2 inches outside the A line except in circular tunnel types where it was 12 inches outside the A line. In supported sections of tunnel as nearly as practicable 12 inches outside of the permanent support above the bottom of wall plates and flush with backs of posts below wall plates except where backs of posts were less than 12 inches from the A line.

The position of the B line relative to the A line was not subject to alteration whatever modifications of section were made, and no additional compensation was allowed for excavation or concrete lining on account of any difference which developed between the volume within these lines and the volume actually excavated, except that a provision was made for payment in the final estimate at the rate of \$3 per cubic yard for the number of cubic yards by which the total actual quantity of concrete in the shaft and tunnel linings might exceed the total theoretic quantity computed as described above.

The C line was specified in lieu of the A and B lines at the bottoms of shafts where the outlines were irregular, and its position was not subject to alteration. No unexcavated material of any kind was permitted to project or remain more than 12 inches inside the C line. The C line where used delimited the excavation and concrete to be paid for the same as in the case of the B line.

Definite thicknesses of lining were shown on the plans of typical shaft and tunnel sections. To meet the different conditions that might be encountered, these thicknesses, that is, the location of the A line, were subject to modification but not to any thickness less than the minimum of 3 inches. The thickness was prescribed as the work progressed. However, if any modification was ordered in any stretch of the excavation after the drilling of trimming holes for the stretch was begun, the yardage of excavation involved in such enlargement was paid for at a price bid therefor. Under these provisions as outlined the contractor could exercise such care as he chose in excavation, balancing the added cost in excavation against the saving in concrete. Owing to care in excavation, the actual average breakage in the tunnel was 10.5 inches outside the A line compared with the 12 inches specified for payment.

The contracts included strict sanitary provisions with reference to the physical and medical examination of employees, the design of quarters for housing them, treatment and disposal of wastes, and the care of stables. Exceptional care was taken to prevent the introduction and spread of malaria, and the State Department of Public Health co-operated to that end by periodical inspections of the camp sites with respect to mosquito breeding, and of the employees themselves with

respect to their past record. The contractor was required to provide adequate medical and surgical care, and to designate one or more approved competent, licensed physicians ready at all times to supply medical and surgical services. An emergency hospital was required at each shaft in addition to miscellaneous first-aid stations. Weekly reports were required from the physicians, setting forth clearly the health conditions of the camps and employees.

The four easterly shafts were located in the watershed tributary to Wachusett Reservoir, and to protect the supply special provisions were made to receive all surface drainage from the camps and tunnel spoil banks, and all pumpage from the shafts, in settling basins, the overflow from which was treated as follows: At Shaft 1, from which only a limited amount of tunnel excavation was done, the entire drainage was cared for by natural filtration through the porous bottom of the settling basin, and there was at no time sufficient pumpage to overflow the settling basin and require the construction of filters. At Shaft 2 slow sand filters were constructed to filter the flow from the settling basin, and the effluent was chlorinated. At Shaft 3 very little tunnel excavation was done, and the overflow was not required to be chlorinated. At Shaft 4 the overflow from the settling basin was chlorinated.

GEOLOGY

The legislation authorizing the construction provided specifically for the collection and publication of data on the geology of the region as indicated by the tunnel excavation. The rock encountered varied from the so-called Fitchburg granite near the east end to the Paxton and Brimfield schists in the central belt. The rock encountered was uniformly sound in the total length of 74,901 feet excavated under the Ware supply contracts. Tunnel support was required in a length of only 322 feet. At several places, aggregating about 3,000 linear feet, where the action of air appeared to affect seams in the rock, necessitating frequent scaling to insure the safety of workmen, stability of the roof was secured, pending the final concrete lining, by coating the roof with Gunitite, usually applied in three courses with an aggregate thickness of about one inch. This method proved so successful that in a subsequent contract for extending the tunnel to the Swift River an item for applying such Gunitite protective coating where ordered or approved was provided for at a bid price.

The rock was generally hard enough so that it could be crushed directly from the spoil banks for use as concrete aggregate for the tunnel lining. A detailed geological profile along the entire length of the tunnel, including the portion now under construction to the Swift River, will be

prepared for publication. Samples of the rock taken at regular intervals have been permanently preserved and stored in cabinets in the Ware River intake building at Shaft 8.

PHYSICAL DATA

The following table presents the physical data with reference to the number of shafts, distance between shafts, and depths sunk through earth and rock to reach the tunnel grade. For convenience of future as well as present reference, the table is extended to include the entire tunnel through to the Swift River.

SHAFT AND TUNNEL DATA

SHAFT No.	Angle	Distance between Shafts (Miles)	Original Surface (Eleva- tion)	Rock Elevation	Earth Depth (Feet)	Tunnel Invert (Grade)	Total Depth (Feet)
1 . . .	—		405.2	373.2		200.00	
2 . . .	14° 59'	1.88	563.4	538.8	32.0	250.00	205.2
3 . . .		1.74			24.6		313.4
4 . . .	—	1.67	723.4	662.8	60.6	384.60	338.8
5 . . .	—	2.20	844.9	822.1	22.8	387.29	457.6
6 . . .	—	2.10	1046.8	1028.0	18.8	390.36	656.4
7 . . .	—	1.75	825.3	796.3	29.0	393.77	431.5
8 . . .	—	1.90	807.4	782.9	24.5	396.82	410.6
		1.24	649.5	646.5	3.0	396.82	252.7
	11° 46' 23"	1.11					
9 . . .	—	2.74	602.8	593.8	9.0	402.77	200.0
10 . . .	—	3.00	814.7	780.9	33.8	406.14	408.4
11 . . .	1° 48' 58"	3.17	684.8	660.9	23.9	409.93	274.9
12 . . .	—	.06	503.7	499.5	4.2	414.05	89.7
Portal . . .	—	.04					
Lower intake .	—	24.60					

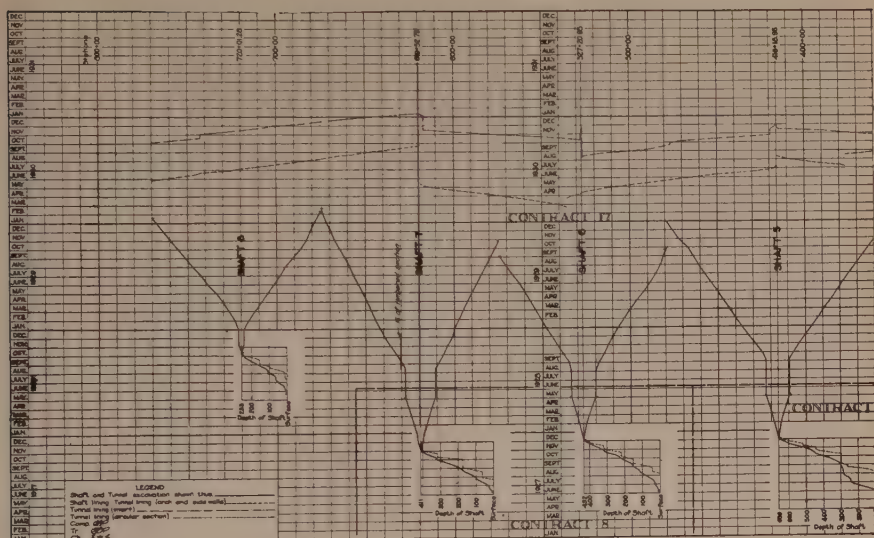
PROGRESS OF CONSTRUCTION

The progress of the work on the eight shafts and fourteen miles of tunnel required for the Ware supply is shown on the accompanying Plate IV. The entire excavation under both shaft and tunnel contracts is included in this comprehensive chart, and at the top is shown the rate of progress obtained in placing, first, the concrete lining of the side walls and arch, and last, the invert.

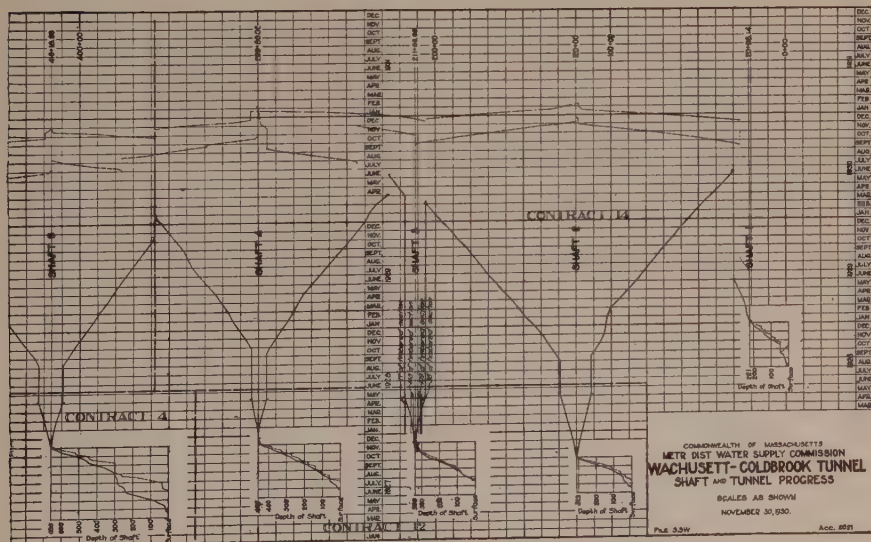
Very little excavation was done from Shaft 1. Instead, the contractor preferred to operate with a small force at this point and to construct the outlet works to Wachusett Reservoir without interference from the tunnel excavation. The contractor elected to postpone the installation of a head frame at Shaft 3, and the character of the rock encountered in the west heading from Shaft 2 and the east heading from Shaft 4 was sufficiently favorable so that he was able to complete the contract without installing additional plant at Shaft 3.

The alignment of the tunnel was carried on by the usual method of dropping two plumb bobs and extending the line thus established into the tunnel by readings on brass vernier scales set in the roof. After the lines had been dropped a sufficient number of times to get an accurate average, these lines were extended as the operations progressed. At the points where the excavations met between shafts, the average difference in line was .59 foot, and in grade, .06 foot.

Crushing, screening and mixing plants for lining the tunnel were set up at Shafts 2, 4, 5 and 7, and the entire tunnel was lined from these points, except that concrete for the invert west of Shaft 8 was mixed at the top of this shaft and dropped through a pipe passing through the plug in the top of the shaft while this plug and other features of the intake works were being built in connection with the construction of the Ware River diversion dam and the siphon spillways. The contractor used three complete tunnel concrete placing plants which were moved along the tunnel as required, taking the mixed aggregates first from one surface plant and then another, as the work progressed. Each tunnel plant included a mixer which received the materials weighed and batched dry in the surface plants, a concrete gun operated by compressed air, designed to deliver at the top of the forms, and 200 feet of side-wall and arch forms which could be collapsed in 20-foot lengths and telescoped ahead to permit the concrete to be poured in one continuous operation without the construction of bulkheads. The general procedure was to start the plant at the most distant point from the shaft supplying the surface materials, to line the tunnel to a point near the shaft, then to



(a)



(b)

partially dismantle the plant so as to turn it around and move it as far as desired, and then to work toward the shaft from the opposite side, or else to haul it through the tunnel to a point where it could continue to work in the same direction but toward some other shaft.

The greatest distance of side walls and arch concreted in one stretch was 11,079 feet, on which the average weekly progress was 834.7 feet. The maximum progress on any one stretch was for a distance of 3,977 feet, on which the average was 994.2 feet per week.

The greatest length of invert concreted in one stretch was 11,020 feet from Shaft 5, on which the average progress obtained was 115 feet per day. The maximum progress on any single stretch was 277 feet per day in a length of 8,857 feet concreted from Shaft 7.

ELECTRIC POWER

Electric power was supplied to the contractors over a 22,000-volt transmission line built by the Commission along the tunnel right of way from a substation near Shaft 1 where the energy was transformed from 66,000 volts. At each shaft it was further transformed to either 440 volts or 220 volts.

The contractors paid for power used, including transformer losses from 22,000 volts, at the rate of $1\frac{1}{2}$ cents per k. w. h.

The following table gives a general idea of the relation between electrical energy consumed and the major items of the work:

Total excavation (cubic yards)	542,000
Total water pumped (million foot-gallons)	1,600,000*
Total concrete in tunnel (cubic yards)	160,880
Total k. w. h. consumed	39,127,000
K. w. h. consumed after excavation was completed and lining begun	12,393,800

* Includes 25 per cent allowance for friction losses.

WACHUSETT-COLDBROOK TUNNEL

Bid Prices of Principal Items and Amounts actually paid for Work, October 27, 1932

Unit	Contract 4 Shaft 5 and Excavation of 1,367 Feet of Tunnel		Contract 8 Shafts 6 and 7 and Excavation of 3,062 Feet of Tunnel		Contract 12 Shafts 2, 3 and 4 and Excavation of 3,810 Feet of Tunnel		Contract 14 Shaft 1 and East Portion of Tunnel, except Portion under Contract 12		Contract 17 Shaft 8 and West Portion of Tunnel, except Portion under Contracts 4 and 8		Total Amounts paid, Tunnel and Shafts, except Super- structures at Shafts 4 and 8
	Bid Price	Total paid	Bid Price	Total paid	Bid Price	Total paid	Bid Price	Total paid	Bid Price	Total paid	
Earth excavation for shaft											
Rock excavation in shafts and tunnel within 50 feet of center line	c. y.	\$1,152	\$6 50	\$3,277	\$10 00	\$11,401	\$8 00	\$13,418	-	-	\$29,248
Excavation in tunnel except within 50 feet of center line	c. y.	14 90	13 65 14 00	375,463	13 50 13 00 13 00	133,625	12 00	38,840	\$12 00	\$57,461	819,005
Drainage in shaft and tunnel	c. y.	-	-	-	10 00 13 00 13 50	304,032	10 75	2,204,812	11 00	2,753,638	5,262,481
Forms for shaft lining	l. f.	22 20	9 75	37,942	15 00	73,503	2 00	67,202	2 00	82,286	305,713
Concrete shaft lining (Shafts 2 to 7)	l. f.	15 75	15 75	12,690	22 00 30 00 20 00	25,064	15 75	3,435	15 75	3,875	55,041
Concrete masonry (Shafts 1, 8).	c. y.	11 55	11 55	21,581	16 00 17 20 15 00	42,415	-	-	-	-	80,492
Forms for tunnel lining	c. y.	-	-	-	-	-	10 00	28,799	10 00	19,475	48,275
Concrete masonry in tunnel	l. f.	-	-	-	-	-	2 60	87,625	3 50	144,088	231,713
Portland cement for concrete and grout	c. y.	-	-	-	-	-	7 50	550,168	8 00	700,206	1,250,375
Permanent timbering in tunnel	bbl.	2 60	2 70	5,831	3 20	11,911	2 65	314,368	2 60	310,238	646,909
Temporary timbering in tunnel	M. F.	-	-	-	-	-	35 00	108	25 00	46	154
All other items	B. M.	-	-	-	-	-	100 00	425	100 00	344	769
Total	-	-	-	\$456,784	-	\$632,727	-	\$3,515,787	-	\$4,127,094	\$9,022,975

Bids ranged from about \$9,500,000 to about \$14,500,000 on the above contracts.

The large apparent saving of actual overestimated costs is due primarily to the small amount of timber required compared to that originally estimated.

COST

The amount paid for sinking and lining the shafts ready for the tunnel excavation averaged \$192 per linear foot, exclusive of engineering and general overhead. The work was done under three contracts as shown in the following tabulation. Shafts 1 and 8 are not shown in the table, since they were included in the tunnel contract and were built at greater cost on account of the special provisions in the case of the Ware River intake at Shaft 8 and the Wachusett outlet at Shaft 1.

AMOUNT PAID FOR CONSTRUCTION SHAFTS

SHAFT No.	Depth (Feet)	Paid to Contractor
2, 3 and 4, aggregating	1,110	\$233,520
5	656	124,230
6 and 7, aggregating	842	142,230
Total	2,608	\$499,980
Average price per foot	—	\$192

These same shaft contracts provided for the excavation of the tunnel for a distance from the bottom of each shaft in order to allow the installation of head frames and timbering for hoists in each shaft under the tunnel contracts after the headings were at a sufficient distance so that the blasting operations would not damage the hoists and other equipment installed at the shaft bottoms.

The amount paid for tunnel excavated under the shaft contracts without the benefit of the equipment installed under the regular tunnel contracts averaged \$107 per linear foot, this being for excavation only, the lining in these previously excavated portions being placed later under the tunnel contract.

The amount paid for excavation and lining under the tunnel contract was as follows:

	Per Linear Foot
Excavation, 66,512 feet, exclusive of the shaft bottoms	\$76 80
Timbering, in only 322 linear feet in the entire tunnel	10
Concrete lining, 74,870 feet, except cement	16 70
Cement	7 95
Forms for lining	3 10
Miscellaneous items, distributed over the entire length	6 10
Total	\$110 75

The last line in the above tabulation, called "miscellaneous items," includes the special outlet at Shaft 1 containing a large 144-inch Venturi meter, steel shaft lining for the upper 95 feet, a special dry pump shaft 220 feet deep alongside the waterway shaft equipped for the installation of a tunnel unwatering pump, foundations for the outlet building, a short outlet channel to Wachusett Reservoir walled with ashlar masonry, a circular tunnel section instead of a horseshoe section for 500 feet near the outlet shaft, all grouting in this section and at the shafts, completing and capping all construction shafts, the special Ware River intake Shaft 8 lined with cast iron, a portion of the substructure of the intake works, all surface sanitary works, including settling basins and filters, the cost of medical and hospital services and cleaning up.

The amounts paid for the tunnel taken as a whole are believed by the writer to include a fair and reasonable profit to the contractor.

The amounts above stated paid for sinking shafts or constructing the tunnel do not include the cost of construction and maintenance of an electric transmission line over the tunnel right of way and a sub-station near Shaft 1. This line was used not only on all the shaft and tunnel contracts, but also to some extent in the construction of the superstructures at Shafts 1 and 8. However, its cost if distributed over the entire length of the tunnel bore only amounts to \$1.60 per foot of tunnel.

The total amount paid for the fourteen miles of tunnel complete, including superstructures at Shafts 1, 4 and 8, and their equipment, grading and landscaping grounds, diversion dam at Shaft 8, engineering and miscellaneous, is as follows:

Electric transmission line, including maintenance	\$119,550
Tunnel and shafts	9,042,400
Ware River intake, diversion dam, superstructure and grading	363,300
Superstructure for access at Shaft 4	5,700
Wachusett outlet, superstructure and grading	83,800
Miscellaneous equipment	78,700
Direct labor and miscellaneous expense	11,400
Subsurface surveys	18,650
Real estate	128,300
Engineering and general overhead	690,000
Total	<u>\$10,541,800</u>

This covers the entire cost to the Commonwealth of the Ware River supply except cost of land purchased for watershed protection, cost of diversion damages and surveys therefor, and small amounts paid for miscellaneous maintenance of real estate and structures, all of which aggregate to date about \$863,000.

WACHUSETT OUTLET WORKS

The construction at the Wachusett outlet works is illustrated on Plate V. Until the Quabbin Reservoir is completed the diversions from the Ware River will flow directly by gravity into Wachusett Reservoir, being controlled only by the gates at the top of Shaft 8 in the Ware River intake works. After the Quabbin Reservoir is completed, gates controlling the flow into Wachusett Reservoir will be

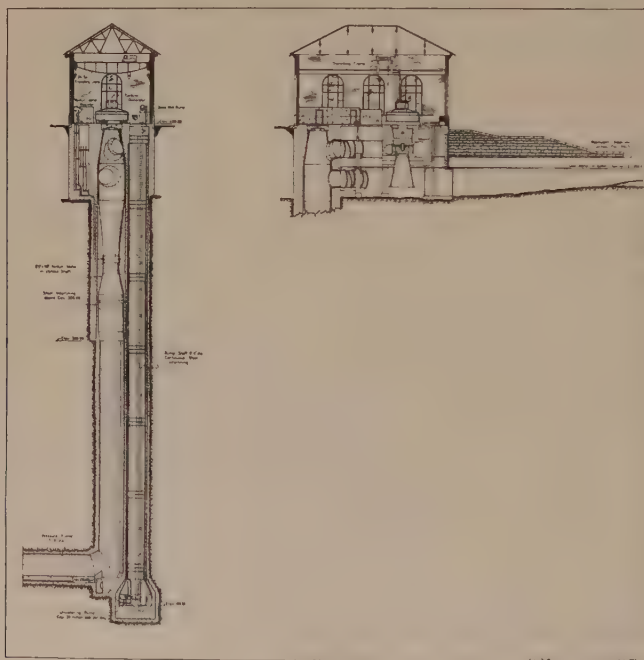


PLATE V

WACHUSETT OUTLET WORKS

(Scale, 1" = 90', approximately)

installed at the downstream end in the Wachusett outlet works. There are several reasons for this arrangement. One is the ease with which gates can be installed there to shut off the discharge of Ware floods and force them west into the Quabbin Reservoir as compared with the impracticability of installing gates in the tunnel at the bottom of Shaft 8 for such purpose. Another reason is the impracticability of installing gates at the Quabbin intake to control the flow into the tunnel on account of the fact that flood flows from the Ware River will frequently be dis-

charged at high rates westerly from Shaft 8 into the Quabbin Reservoir and must have a free outlet there. Another reason for the control at Shaft 1 is the opportunity after the reservoir is built to generate electric power by utilizing the fall of 135 feet between the Quabbin and Wachusett reservoirs. In order to avoid a long, deep, open discharge channel at hydraulic grades in or alongside the Quinapoxet River, from the end of the tunnel to the Wachusett Reservoir, it was found best to depress this end of the tunnel as shown on Plate II and to design it to take the maximum possible static pressure with the outlet gates closed. Shaft 1 was therefore located where sound rock was found near the surface, and was built to withstand this maximum pressure, as well as that during tunnel unwatering operations; 500 feet of tunnel adjacent to the shaft was built of circular section and was grouted solidly to the rock.

The waterway at Shaft 1 is lined with a continuous riveted steel pipe, caulked to secure watertightness, for a depth of 95 feet from the top of the shaft in order to prevent the pressure after installation of the power plant from lifting the top of the shaft under any conditions and cracking or causing other damage to the building foundations. To prevent corrosion this steel pipe is lined with concrete. The waterway is shaped to form a large Venturi meter, the diameter of the upstream ring being 12 feet, and the diameter of the throat 7 feet 6 inches. Alongside the waterway shaft is a dry well or pump shaft 8 feet in diameter, enlarging to 12 feet in diameter at the bottom to form a pump chamber. This shaft and pump chamber are encased throughout the entire depth with a continuous steel circular lining to prevent seepage of water into the shaft (the head at bottom of the shaft will be about 200 feet before and 335 feet after installation of power plant). The steel lining is lined with cement mortar to prevent corrosion. Access to the bottom of the shaft is obtained by a steel ladder with platforms every 33 feet, heavy loads being handled in and out of the shaft by the bridge crane in the superstructure. The pump installed in this well for unwatering the tunnel is a single stage, centrifugal pump, direct connected to a 900-horsepower induction motor. Although the steel lined shaft is practically bottle-tight, there is considerable condensation and some drip from the walls at the bottom of the shaft. The motor is designed with special waterproof insulation and drip-proof casing. However, when not in use it is stored on the main floor at the top of the shaft. The pump, however, is left at the bottom of the shaft with the entire casing, when not in use, filled with oil. The pump shaft as well as the flange of the flexible coupling is of stainless steel. There are two valves on the 20-inch pump

suction, the one nearer the tunnel being of solid bronze throughout, bolted to the suction pipe leading from the tunnel with steel bolts entirely embedded in the concrete. To shut this valve in an emergency, a continuous chain pull is carried to a gate stand at the top of the shaft in guides.

To keep the pump well itself unwatered, as well as to empty it in case it should be filled by any accident, an unwatering pump of the deep-well type was installed on the main floor at the top of the shaft. This pump discharges through a 6-inch pipe hung on the inside wall of the shaft close to the access ladder. The discharge of the main unwatering pump at the bottom of the shaft is through a 16-inch, cast iron pipe embedded in the concrete lining of the shaft. This discharge pipe is carried through the foundations of the superstructure, and discharges on the reservoir side of stop logs which must be inserted in the outlet channel whenever the tunnel is unwatered. An additional 16-inch pipe embedded in the concrete shaft lining supplies air at the rate of 6,000 cubic feet per minute from a blower on the main floor to the bottom of the pump well at the motor.

TUNNEL UNWATERING

Following the first season's operation of the Ware River intake works, the pump and motor were installed in the pump well at Shaft 1 during the summer of 1931, and the tunnel was unwatered for inspection in September.

The motor was first thoroughly dried out by the use of a low voltage current for several days. The pump was then started and operated until the gage glass provided in the pump chamber showed the unwatering to be practically completed. The discharge on the pump was then throttled and men were lowered into the waterway shaft. The tunnel was found to be in excellent condition, there being no evidences of damage to the lining at any point.

WARE RIVER INTAKE WORKS

The special construction required for the Ware River intake works at Shaft 8 is shown on Plate VI. The diversion dam is designed as a spillway, consisting mainly of a thin circular arch with a radius of 52.5 feet, and a crest at elevation 657 above Boston City Base. The length of the spillway is 174 feet at this elevation, including 34 feet along the top of abutment sections. The diversion is accomplished by nine siphon spillways with crests at an elevation 1 foot lower than the spillway of

the diversion dam. These siphons discharge into a central pit in the building, in which the water level is controlled by four butterfly valves of the Dow-disc type, which are set directly over the shaft in a floor or plug of reinforced concrete 9 feet thick, and throttle the discharge into the shaft, automatically maintaining the correct rate of diversion through the spillways by controlling the head on the spillways and at the same time creating a water seal to prevent the entrance of air into the tunnel. The operation is entirely automatic, designed to divert all flood flows in excess of a rate of 85,000,000 gallons daily into the shaft, and to prevent any diversion when the flow in the river is less than this limiting rate.

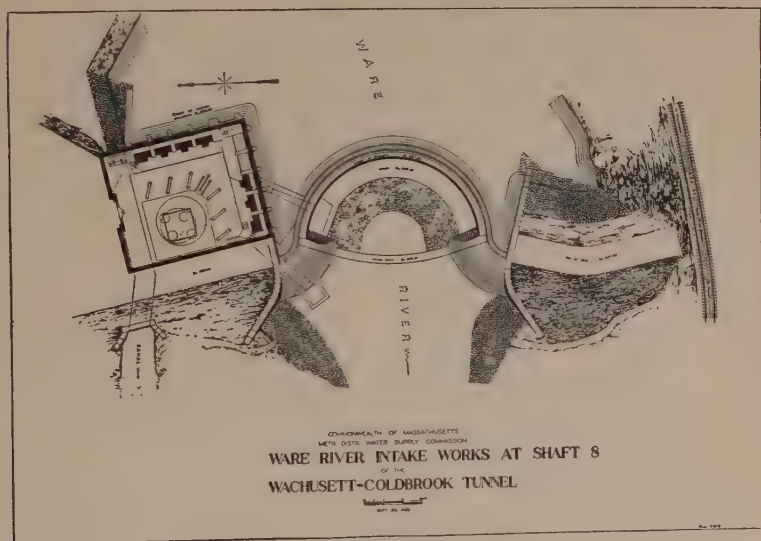


PLATE VI

(Scale, 1" = 100', approximately)

OPERATION OF INTAKE WORKS

The method of operation of the intake works is illustrated in the diagram shown on Plate VII. The diversion of Ware River water into Wachusett Reservoir came at a most opportune time, as this reservoir in February, 1931, was at the lowest point in its history, namely, 45 feet below normal high water, the available storage having been reduced since June, 1929, from 55,000,000,000 gallons to 11,000,000,000 gallons. The addition to this storage of practically 13,000,000,000 gallons from the Ware River, equivalent to about three months' supply to the Metro-

politan District, coupled with a spring flow from the Wachusett watershed itself in excess of normal, ended the immediate menace of a water shortage.

The intake works at Shaft 8 and the Wachusett-Coldbrook tunnel were completed sufficiently on March 1 to allow the diversion to be made. The superstructure of the intake building had not been erected, but the heating plant had been installed in the basement, and small temporary wooden housings had been built over the operating panel, siphon break pipes, switchboard and other apparatus above the main

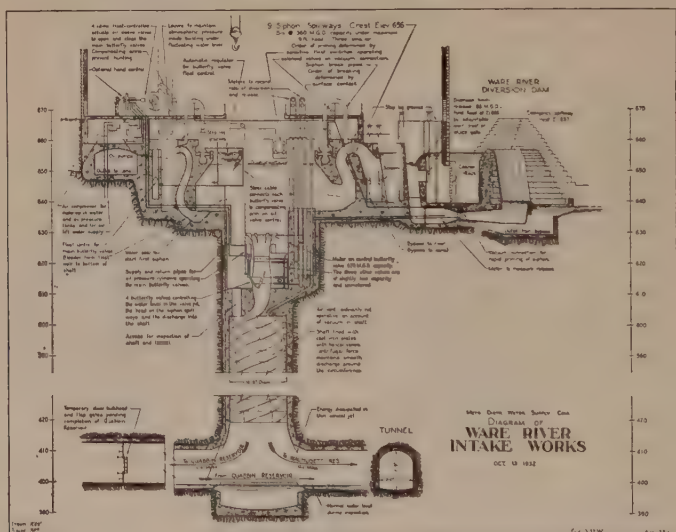


PLATE VII

floor of the building in order to commence operations and obtain the first water available.

The diversion dam across the river just downstream from the tunnel shaft acts as a spillway to pass such occasional flood peaks as may exceed the capacity of the diversion works, or, during the summer months, from June 15 to October 15, to pass the entire flow of the river. From October 15 to June 15, or during the allowable period of diversion, the normal river flows up to 85,000,000 gallons daily pass over a weir in the foundations of the intake building, through a 52-inch Venturi meter, back into the river below the spillway. The specified 85,000,000 gallons daily raise the pond level to 1 foot below the crest of the main spillway, this foot leeway being thus available in the operation of the diversion works.

The nine siphon spillways constructed in the foundation walls of the intake building between the river and the shaft, through which the diversion is accomplished, vary in capacity from 60 to 550 cubic feet per second under a 9-foot head. The crests of these siphons are 1 foot below the level of the main spillway, and siphon break pipes are set at this level so that whenever the pond is lower than this level, which corresponds to 85,000,000 gallons daily flow released down the river, the siphons are automatically broken and no water can be diverted into the tunnel. On a rising flood the rapid priming of the siphons in succession, one after the other up to the required capacity, is assisted by a series of float switches, specially designed for sensitiveness, which automatically connect each siphon in its turn to a vacuum pipe system in the building, which is tapped into the 52-inch Venturi meter just below its throat, thus maintaining a vacuum in the entire system. The central pit over the shaft into which the nine siphons discharge is automatically kept at the level desired at all times to seal the shaft against the entrance of air and to back the water up to the required head on the siphon spillways.

The works are designed with an ultimate capacity of about 2,000,000,000 gallons per day. Such a flow, after the Quabbin Reservoir is completed, will divide at the bottom of the shaft and flow part to the Quabbin Reservoir and part to the Wachusett Reservoir. Under the extreme rate of diversion, the entire 9-foot head on all spillways will be required. Until the Quabbin Reservoir is completed, the present capacity of the works, flowing only in an easterly direction toward the Wachusett Reservoir, is limited to a little over half this quantity. In ordinary operation only a small head is required on the siphons.

The four valves of the Dow-disc type above referred to are operated by oil pressure cylinders capable of taking 250 pounds per square inch oil pressure, but normally requiring only about 50 to 75 pounds. The valves are normally under a water head of about 40 feet, and the top of the highest bell-mouth entrance is always submerged at least 18 feet and usually 25 feet. Only one of these valves, 6 feet in diameter, is ordinarily used, since it can take care of all flows up to about 600,000,000 gallons per day. A 120-inch Venturi meter to measure the flow is built into the bell-mouth entrance above this valve. The three other valves are each 5 feet in diameter and are opened automatically one after the other as soon as the capacity of the first large valve is exceeded.

The discs of these valves are held by the oil pressure at just the right angle to pass the available flow in excess of 85,000,000 gallons daily in the river, and to hold the water in the pit at just the right level so that the siphons will pull this quantity from the river. Each butter-

fly valve responds under the oil pressure to the exact setting of a sleeve valve on the oil pressure and return lines, all the sleeve valves being grouped together on a small operating panel in one corner of the main floor of the building. Except when under manual control, this setting is changed automatically, being connected to the cross head of the oil cylinder of the butterfly valve through a small steel cable running through the building over pulleys as required and through the water in the pit. Thus the only mechanical connection between the valves in the bottom of the pit and the operating panel is by the cable, the flexibility of which accommodates itself to the swirl of water in the pit.

The water is discharged from these valves through a nozzle and impinges tangentially, at an angle of about 30° with the horizontal, at high velocity against the cast iron lining of the shaft. The helical vanes on this lining cause a rotation of the falling water which is pressed by centrifugal force into a thin film against the cast iron wall of the shaft. That the entrance of air into the tunnel is effectively prevented by the valve-controlled water cushion at the top of the shaft is shown by the high vacuum observed in the shaft.

The final design of the shaft lining was based on very satisfactory results obtained from the test of a model of the shaft and its tunnel connections. This model was one-twentieth the actual size of the shaft, and was built and tested at the Alden Hydraulic Laboratory of the Worcester Polytechnic Institute under the direction of Prof. Charles M. Allen.

The valve pit or basement of the diversion works was filled for the first time on March 20, 1931, and on March 21 water was diverted into the tunnel and the works were operated whenever the flow in the Ware River exceeded 85,000,000 gallons a day, except in the period from June 15 to October 15, inclusive, when in conformity with the requirements of the War Department no water was diverted.

The maximum rate of diversion occurred on Saturday, April 4, when water was dropped into the tunnel at an average rate for the twenty-four hours of 627,000,000 gallons, or about 30 tons per second. At moderate rates up to 250,000,000 gallons per day, the water drops the entire distance, down the spirally lined shaft, to the crown of the tunnel. As the rate increases to about 300,000,000 gallons per day, the water level in the tunnel rises and seals the bottom of the shaft.

Observations during the diversion at a gage provided for the purpose indicate that a vacuum equivalent to about 25 feet of water is created and maintained in the shaft at all diversions in excess of about 300,000,000 gallons per day. This vacuum causes the water level to

rise in the shaft so that, for example, water diverted at the rate of 627,000,000 gallons per day, the maximum above referred to, after passing through the regulating valves and the plug in the top of the shaft and whirling around the shaft through a height of approximately 100 feet of rarefied air, strikes a water cushion approximately 100 feet deep in the lower half of the shaft. On the other hand, smaller rates of flow of, say, 250,000,000 gallons per day after passing through the regulating valves whirl through a height of about 200 feet into a water cushion about 15 feet deep.

During the first month the works were operated largely by manual control in three shifts, at least one operator being on hand at all times to make adjustments. Commencing April 19, 1931, the works were successfully placed in automatic operation, with an operator on hand only during the ordinary working hours of the day. Diversion of the allotted flood flows continued without attendance nights, Sundays and holidays, entirely automatically except when manual control was cut in on several occasions during the daytime for special purposes.

The operation was continued successfully during the following season and the spring of 1932.

From May 20, 1930, to March 21, 1931, the flow of the Ware River at no time reached the point where any water could have been diverted under the law; 12,813,900,000 gallons were diverted during the season of 1930-31, and 9,597,100,000 during 1931-32.

During five days in the spring of 1931 the height of water was measured at Shafts 1, 2, 3 and 7, while measured flood flows of about 500,000,000 to 600,000,000 gallons daily were diverted, and it was found that the coefficient of discharge was about 150 to 155 in the Chezy formula, corresponding to Kutter n = about .012. The hydraulic gradients shown on Plate II are drawn for n = .013, which is expected to safely represent the future condition which can be maintained. As indicated on Plate II, the discharge shown should be increased by 9 per cent to give the flows now obtained in the tunnel when new and clean. The maximum capacity of the tunnel was reached for a few minutes on April 1, 1932, when about 1,200,000,000 gallons daily were discharged easterly from Shaft 8.

TUNNEL BULKHEAD

In order to permit the extension of the tunnel westerly to the Swift River without interference with the operation of the Ware River diversion, the tunnel was excavated for a distance of 4,998 feet west of Shaft 8, and at a point 2,200 feet west of the shaft a massive steel bulkhead was

constructed with two hinged doors capable of withstanding the total head of about 250 feet that might result during the diversion of Ware floods of unusual magnitude. These doors are in effect check valves, and after the entire tunnel is completed and until the Quabbin Reservoir is ready to store water, they will continue to prevent floods from the Ware River from flowing westerly. At the same time the swinging doors will allow a flow of water from the Swift River into Wachusett Reservoir if it should be necessary to take such a flow in an emergency. These doors are about 4 feet by $3\frac{1}{2}$ feet, and each is hinged at the side with two hinges of stainless steel, the alignment of the hinge pins being slightly off the vertical so that in spite of their great weight the doors close very easily. For watertightness, a rubber gasket is embedded around the entire edge, and the hinges are especially designed so that the pins are not sheared during the compression of the gasket.

TUNNEL SPILLWAY

The use of controlling gates in the Wachusett outlet at the top of Shaft 1 makes it physically possible for careless or improper operation to build up very high pressures in the tunnel. For example, if the outlet gates should be closed tight at a time when flood flows were being diverted at a very high rate from the Ware River, it would be possible to raise the hydraulic gradient practically to the level of the intake valves at Shaft 8, or 200 feet above the level of Wachusett Reservoir. To prevent such a condition, the top of Shaft 2 has been finished as a spillway by capping the shaft with a concrete floor 4 feet thick and by building in this plug in addition to air vents four circular openings 4 feet in diameter closed with heavy steel covers hinged at one side. A relatively small head of water will lift these covers and vent the water pressure as required. Although these covers are too heavy to be lifted by malicious trespassers, the top of the shaft is protected by a heavy structural steel fence $8\frac{1}{2}$ feet high which would not obstruct the spillway discharge but would prevent tampering with the covers. The effect of this spillway is illustrated on the chart of tunnel gradients on Plate II.

YIELD OF OLD AND NEW SOURCES

The following table shows the safe yield of all the district sources including the completed Ware and Swift development. Excellent records of the run-off of the south branch of the Nashua River on which the Wachusett Reservoir is built are available commencing with 1897.

Records of the flow of the Ware and Swift rivers are available beginning in 1913, and a very good estimate can be made for years previous to these records by comparisons with the near-by Wachusett watershed. The so-called safe yield shown in the table is in every case the yield that could have been maintained continuously from 1897 to date, if the works as now proposed had been constructed at that time, and if the district had then been able to consume these higher rates.

WATERSHED	Drainage Area (Square Miles)	YIELD (MILLION GALLONS PER DAY)		
		BEFORE COMPLETING QUABBIN RESERVOIR		AFTER COMPLETING QUABBIN RESERVOIR
		Leaving 20 to 25 Billion Gallons in Storage at All Times in Wachusett	Drawing Wachusett nearly to the Bottom if and when Necessary	About 40 Billion Gallons can be left in Wachusett at All Times
Wachusett-North Sudbury system *	136.52	119	127	133
South Sudbury System:				
Whitehall-Hopkinton Reservoir .	10.61	9	—	3
Ashland Reservoir	6.43	5	—	—
Cordaville Pumping Station .	17.24	5	—	—
Lake Cochituate	17.58	8	—	—
Ware River	98	—	29	40
Quabbin Reservoir	186	—	—	154
Total	—	—	—	330

A greater yield is obtained from the Wachusett Reservoir itself, after the Quabbin Reservoir is built, on account of the opportunity to operate the two reservoirs together advantageously. On the other hand, the relative value of such emergency sources as Lake Cochituate and the South Sudbury system will be decreased when the new supply is completed, since the occasions requiring their use will be few and far between and their advantage expressed in terms of average yield correspondingly small. The yield shown in the table for the Ware supply is the net yield after meeting the requirements of the War Department

* Includes 20.7 square miles from which Worcester may pump a maximum of 10,000,000 gallons daily.

that no diversion shall be made between June 15 and October 15. Also, the yield shown for the Swift is the net yield after meeting the legislative requirement that a sufficient amount shall be released from storage at all times to maintain a flow of 20,000,000 gallons daily in the river at Bondsville about five miles downstream from the main dam, and also the further requirements of the War Department that there be released during the period from June 1 to November 30 each year, from the waters impounded in the Quabbin Reservoir, a flow of 70 cubic feet per second during each day when the flow of the Connecticut River at Sunderland, Massachusetts (drainage area 8,000 square miles), is less than 4,900 cubic feet per second and more than 4,650 cubic feet per second, and that there be released, when the flow is 4,650 cubic feet per second or less, 110 cubic feet per second.

CONTRACTORS' ORGANIZATIONS

The work under Contract No. 4, for the construction of Shaft 5, and that under Contract No. 8, for the construction of Shafts Nos. 6 and 7, was done by James J. Coughlan and Sons, Inc., of Boston. That under Contract No. 12, for the construction of Shafts Nos. 2, 3 and 4, was done by the Dravo Contracting Company of Pittsburgh, Pennsylvania.

The east and west portions of the tunnel, including therein Shaft No. 1, the Wachusett outlet, and Shaft No. 8, the Ware River intake, were built under Contracts Nos. 14 and 17, respectively, by the West Construction Company of West Rutland, Massachusetts. This company was assignee of the original contracts which had been awarded in the case of No. 14 to J. P. Porter & Sons of Portland, Oregon, and in the case of No. 17 to Coughlan & Porter of Boston, Massachusetts. Arthur C. Dennis was general manager for the West Construction Company until January, 1930, when he was succeeded by William J. Smail.

THE COMMISSION AND ITS ENGINEERING ORGANIZATION

The Metropolitan District Water Supply Commission was organized in July, 1926. It is composed of three members: Davis B. Keniston, chairman, and Charles M. Davenport and Thomas D. Lavelle, associate commissioners. Frank E. Winsor is chief engineer, Karl R. Kennison is designing engineer and principal assistant to the chief engineer, Charles L. Coburn and Stanley M. Dore, assistant designing engineers, and Walton H. Sears, mechanical engineer. The field forces are in

charge of three division engineers: William W. Peabody, in charge of the Wachusett-Coldbrook division of the Quabbin Aqueduct, Richard R. Bradbury of the Coldbrook-Swift division of the Quabbin Aqueduct, and N. LeRoy Hammond of the Quabbin Reservoir division. X. Henry Goodnough, J. Waldo Smith and Charles T. Main are consulting engineers on the new water supply from the Ware and Swift rivers.

OF GENERAL INTEREST

PROCEEDINGS OF THE SOCIETY

MINUTES OF MEETINGS

Boston Society of Civil Engineers

NOVEMBER 22, 1932. — A regular meeting of the Boston Society of Civil Engineers was held this evening in Chipman Hall, Tremont Temple, and was called to order at 7.15 P.M. by the President, Ralph W. Horne. About 85 members and guests were present. The usual buffet supper preceding the meeting was attended by 47 persons.

The President announced the death of the following: Harrison W. Haywood, died October 18, 1932, a member since December 21, 1910; Morris Knowles, died November 8, 1932, a member since November 21, 1893; John O. DeWolf, died November 17, 1932, a member since May 19, 1897.

The Secretary reported that the following were elected to membership by the Board of Government on November 22, 1932:

Grade of Student Members: Neil B. Faunce, William H. Kelly, Jr., Wilfred Pitts.

At the previous meeting of the Society held on October 19, 1932, a vote was passed regarding the use of the current income from the Permanent Fund. A similar vote was necessary at this meeting, therefore the following vote was passed:

"*Voted*, That the Board of Government be authorized to use so far as necessary the current income from the Permanent Fund for current expenses of the Society."

The President then introduced as the speaker, Prof. Daniel C. Sayre, assistant professor of the aeronautical engineering department at Massachusetts Institute of Technology, who gave a talk on "Weather and Blind Flying."

Professor Sayre described the flights that are made to obtain meteorological data. At 8 o'clock each morning, at the East Boston Airport, Technology's "Flying Laboratory" — a plane piloted by Professor Sayre — climbs three miles into the sky in order that upper air conditions may be studied. The results of this atmospheric research are used by the Institute's meteorological division in its weather forecasts and weather analyses. In addition to the extensive apparatus needed for meteorological work the plane is equipped with every possible navigation aid to assist in "blind" flying. Professor Sayre described the daily operation of these upper air flights in a non-technical manner. Typical instruments used in these flights were displayed and explained by the professor.

A description of the methods of assembling data and interpreting meteorological conditions to formulate weather forecasts was given by Prof. Carl-Gustaf A. Rossby, professor of meteorology, in charge of the department of meteorology at the Massachusetts Institute of Technology.

The meeting adjourned at 9 P.M.

EVERETT N. HUTCHINS, *Secretary*.

Designers Section

NOVEMBER 9, 1932. — The regular meeting of the Designers Section was

called to order by the Chairman at 6 P.M. in the rooms of the Engineering Societies of Boston.

The minutes of the October meeting were approved as read.

Mr. Ralph Horne spoke briefly of the Emergency Planning and Research Bureau, Inc., its work and its need of funds for the winter.

Mr. E. A. Dockstader of Stone & Webster was introduced by the Chairman. Mr. Dockstader gave a very comprehensive discussion of the "Design and Construction of Reinforced Concrete Chimneys." He reviewed the Standards of the American Concrete Institute for Reinforced Concrete Chimneys, which are soon to be published, and gave many interesting personal experiences.

After a general discussion the meeting adjourned at 8 P.M.

Twenty-three members and guests were present.

H. G. DRESSER, *Clerk.*

APPLICATIONS FOR MEMBERSHIP

[November 20, 1932]

THE By-Laws provide that the Board of Government shall consider applications for membership with reference to the eligibility of each candidate for admission and shall determine the proper grade of membership to which he is entitled.

The Board must depend largely upon the members of the Society for the information which will enable it to arrive at a just conclusion. Every member is therefore urged to communicate promptly any facts in relation to the personal character or professional reputation and experience of the candidates which will assist the Board in its consideration. Communications relating to applicants are considered by the Board as strictly confidential.

The fact that applicants give the names of certain members as reference does not necessarily mean that such members endorse the candidate.

The Board of Government will not consider applications until the expiration of fifteen (15) days from the date given.

For Admission

SEXTON, THOMAS HENRY, Brighton, Mass. (Age 52, b. Boston, Mass.) Attended lectures on surveying, use of instruments and higher mathematics given by the Lowell Institute, 1898-99. Employed by the city of Boston, engineering department, as rodman, 1896-99; instrumentman, 1899-1904; assistant engineer, 1904-08; was then transferred to the bridge service as deputy superintendent and commissioner for Boston on the Cambridge Bridge Commission, 1908-09; from 1909 until the Public Works Department was formed was engineer of bridges; in 1911 was appointed supervisor of bridges, and still retains that rating and duties. Refers to *W. H. Ellis, F. H. Fay, N. J. Holland, C. M. Spofford.*

ADDITIONS

Member

E. B. MYOTT, Fay, Spofford & Thorndike, 44 School Street, Boston.

Student Members

ROBERT E. BALMER, Jr., 17 Eden Street, Salem, Mass.

REGINALD A. BARRON, 153 Naples Road, Brookline, Mass.

JOHN M. CHASE, 251 High Street, Newburyport, Mass.

CHARLES W. CROUCH, 118 Hemenway Street, Boston, Mass.

ROLF E. HAMSTROM, 46 Fairfield Street, Portland, Maine.

JOSEPH J. MACAIONE, 8 Boston Street, Lynn, Mass.

WARREN E. MARSTON, 28 Fairmount Street, Dorchester, Mass.

WILBUR C. NYLANDER, 175 Park Avenue, Arlington, Mass.

LESTER S. PERRY, 14 Warner Street, Somerville, Mass.

RAYMOND C. PRESSEY, 18 Savoy Road, Salem, Mass.

JOHN H. WAKENIGG, 153 Naples Road, Brookline, Mass.

DEATHS

MORRIS KNOWLES . November 8, 1932

JOHN O. DeWOLF . November 17, 1932

BOSTON SOCIETY OF CIVIL ENGINEERS

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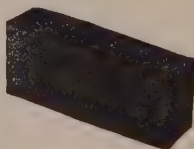
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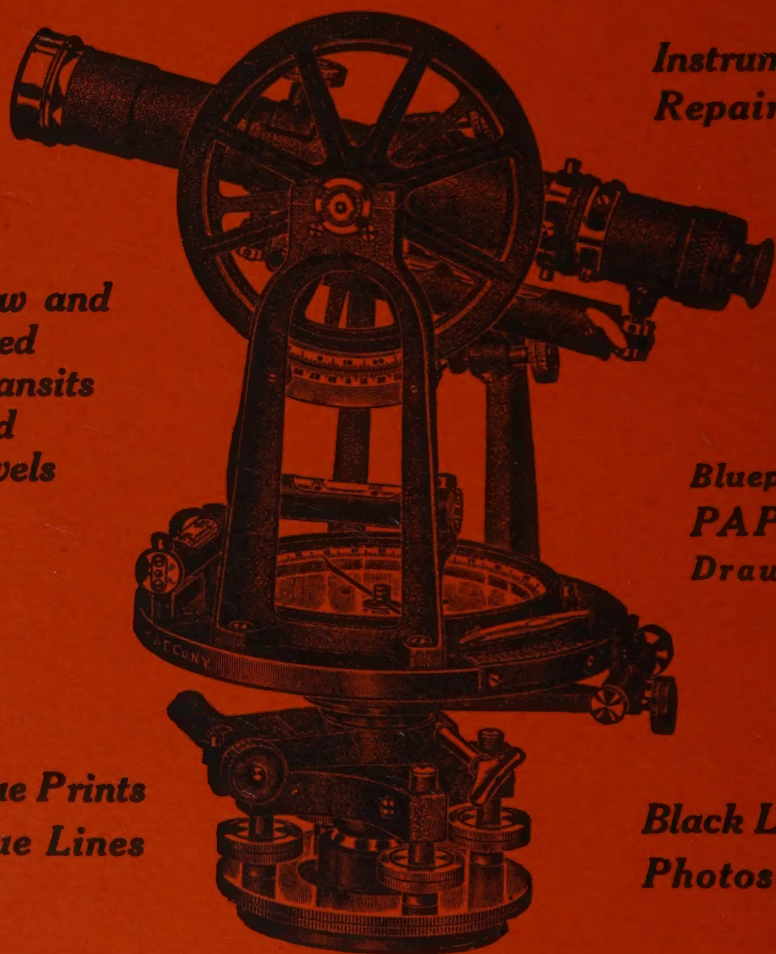
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